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Conceptualising a GIS-based risk quantification framework for fire spread in informal settlements: A Cape Town case study

Samuel Stevens[a*], Lesley Gibson[a], David Rush[a*]

[a]School of Engineering, University of Edinburgh, UK, s.stevens@ed.ac.uk, Lesley.gibson@ed.ac.uk, d.rush@ed.ac.uk

*Corresponding Author

Highlights

- GIS-based risk model for evaluating fire risk in informal settlements
- Comparisons made with fire history data for informal settlements in Cape Town
- Settlement layout is critical in influencing the development of large fires
- Additional framework for infrastructural and environmental risk factors

Abstract

Informal settlements are home to approximately one billion people globally and are growing due to rapid urbanisation in less economically developed countries. Their dense layouts, often combined with light, combustible building materials make them highly vulnerable to fires. In some cases fires have spread through hundreds or thousands of homes in a single fire, rendering the inhabitants homeless. Tackling this issue requires a sound understanding of the many spatial factors which can contribute to fire spread between individual dwellings and into the wider settlement. This paper presents initial methods for assessing and quantifying fire risk in informal settlements due to a variety of spatial factors in the case of Cape Town, South Africa – a city which has a notable history of devastating informal settlement fires. GIS techniques were used to obtain data to build a model for the quantification of risk imposed by the settlement layout with respect to three key metrics; dwelling spacing, edge density and critical patch size. The results of the risk model and data of past fires suggest that the settlement layout is a critical factor in determining the ability of large fires to establish within a settlement. A framework for additional infrastructural and environmental risk is also presented, identifying the need for a wide-ranging interdisciplinary approach to the problem of urban fires.

Keywords: informal settlements; fire risk; GIS analysis

1 Introduction

Informal settlements – which may also commonly be known as slums, shanty towns or favelas – are home to approximately 1 billion people globally [1]. Though the percentage of population living in these settlements is decreasing, absolute figures continue to grow, with estimates suggesting there will be 1.2 billion people living in informal settlements in Africa alone by 2050 [1]. These settlements have a particular vulnerability to fire. In recent years, individual informal settlement fires have rendered many thousands homeless, including 9,700 in Imizamo Yethu, Cape Town [2], 15,000 in Manila [3] – both in 2017 – and a reported 10,000 in Chalantika, Dhaka in 2019 [4]. Clear-up and rebuilding from the single 2017 Imizamo Yethu fire has cost an estimated $8 million to date [2].

At the level of an individual informal dwelling, it has been shown experimentally that a fire can grow to involve the full dwelling in less than 90 seconds [5], with burnout and collapse occurring in as little as 2-5 minutes [6]. Recent tests have also shown that from the point of flashover in one dwelling, a fire can spread to, and reach flashover in, two subsequent dwellings in as little as 4 minutes [7]. This represents an extremely rapid fire development when compared with a typical compartment fire in the formal built environment, and is a significant danger to residents.

However, the potential for a fire to develop from single dwelling or a small cluster of dwellings to the scale of an entire settlement is currently poorly quantified. Statistics available for fires in Cape Town over the period 2009-2015 show that the average fire extended to less than 7 dwellings [8]. Yet, the city's informal settlements still experienced at least one fire involving 20 or more dwellings per week on average [9]. There is a clear discrepancy between daily small fires and the less-frequent large fires which can destroy hundreds of homes.

Dwellings are usually crude structures, with a timber frame and cladding built from corrugated steel sheeting, plastic sheeting or timber [5,6,10]. Residents may insulate their homes by adding internal cardboard or timber board, and reduce permeability of the walls by stuffing any holes with paper.

The combination of readily combustible materials, lack of space between dwellings and exposure to high winds is predicted to contribute to fire spread through a settlement in a manner similar to wildfire spread [5]. Intuitively, settlement density – in terms of dwellings per area – has been postulated as determining the severity of fires, but, taken independently from other factors, has shown only a very weak correlation with fire size [11]. Given the scale of these fires, it is difficult to test these factors experimentally. Yet, better understanding is required to establish how and why such large fires can occur, and to implement mitigation strategies.

GIS-based analysis can play a vital role in this by helping to formulate risk quantification techniques to compare settlements against one another. GIS-based methods are commonplace in previous fire risk quantification studies in the field of both urban fire [12–15] and wildfire [16–19]. However, the complexity of quantifying informal settlement fire risk is exactly that these fires may exhibit characteristics of both standard compartment fire dynamics and wildfire dynamics. No studies have yet made the connection between the two. Existing urban GIS based fire-risk analyses in non-informal contexts justifiably tend to neglect the possibility of fire spread between buildings. Thus, a new conceptualisation of fire risk is required for informal settlements.

Informal settlements are predominantly found in low- and middle- income countries, where reliable data sources are often not easily accessible or in some cases lacking. Cape Town has been selected as a case study due to the availability of fairly reliable GIS data [8,20] and the fact that the founding studies concerning informal settlement fires address it in the South African context [2,5–7,11,21]. This paper presents the case of Cape Town's informal settlements and the role of a high resolution digitised dwelling footprint dataset in establishing the foundation of risk quantification for informal settlements. It proposes a simple multiplicative risk model to quantify fire risk presented by the layout of dwellings within a settlement. It also establishes a framework into which other risk factors can be built in light of future work, acknowledging that current understanding of the fundamental fire dynamics in informal settlement fires is not fully developed.

2 Method

As noted, the number of dwellings in a given area does not necessarily correlate strongly to the potential for severe fires as initially studied by Smith [11]. It is proposed that more rigorous methods of quantification can contribute to better understanding of the present fire risk. The method applied by Smith does not necessarily infer any information about how dwellings are spaced and grouped together within a settlement. These are factors which are key to understanding fire spread and, with good quality GIS data, can be easily quantified.

This work made use of an existing high resolution (±8cm), manually-digitised GIS dataset of informal dwelling footprints in the City of Cape Town [dataset] [22]. Three metrics are proposed below to quantify risk, developed from the data and intended to quantify specific characteristics of a settlement's layout. These metrics were calculated for the 291 distinct 'informal settlement areas' (ISAs) across Cape Town as contained in the dataset. All three metrics are aimed at quantifying spatial characteristics of the layout of dwellings within settlements. At this stage the inclusion of additional environmental and infrastructural metrics faces a gap in knowledge and data as discussed in Section 4, and would thus be unreliable to include currently. The calculation of metrics and subsequent production of non-dimensional risk scores (X) for each ISA was conducted using the following theory and methods.

2.1 Average minimum distance to nearest neighbour

Fire is enabled to spread if dwellings are within a sufficient proximity, predominantly due to radiative heat transfer and direct flame impingement. Generally, the closer a dwelling is to an adjacent fire, the quicker it will ignite, though the time to ignition is also governed by the incident heat flux and the orientation of the dwelling towards the fire. The overall model for radiative heat transfer given in Drysdale [24] implies the relationship between incident radiative heat flux ($\dot{q}"$) and distance from emitting source (*r*) is of the following form:

$$\dot{q}" \propto \frac{1}{r^2} \tag{1}$$

Drysdale also gives a model for the time to ignition (t_{ig}) of thermally thin materials which implies:

$$\dot{q}" \propto \frac{1}{t_{ig}} \tag{2}$$

Therefore,

$$t_{ig} \propto r^2 \tag{3}$$

This forms a very basic foundation for the rate of fire spread between adjacent informal dwellings. For informal settlement fires, the distance between dwellings and the distance of radiative heat transfer are not equal since there will be a plume of flames projected from any vents – open windows or doorways – in the dwelling. This plume may directly impinge the edge of an adjacent dwelling if it is in sufficient proximity, but primarily adds to the thermal radiation emitted by the burning dwelling. The extent to which this plume protrudes from the burning dwelling varies with the size and shape of the opening from which it flows, as well as if there is any wind-assisted through draft. The effects of these on risk are complex but Wang et al. model simplified relationships for scenarios with no through draft [25]. These suggest the incident heat flux experienced by an adjacent dwelling is at a constant maximum up to 0.6-1.3m from the burning dwelling depending on opening characteristics, dropping as an inverse square function to effectively 0 kW/m^2 at some distance from the dwelling. A thermally thin model has been selected due to the prevalence of thermally thin lining materials as discussed earlier, but this does not guarantee that in a real fire a thermally thin material will always be the point of ignition. However, Drysdale's corresponding model for the ignition of thermally thick materials would lead to a relationship of the form:

$$\dot{q}'' \propto \frac{1}{r^4} \tag{4}$$

Thus, using the thermally thin model provides a conservative quantification of risk.

In real fires, the specific location of the vent on the wall of the dwelling will determine which adjacent dwellings will be exposed to the flame plume, and how far they will be from the plume. However, vent locations cannot be detected remotely by satellite imagery. This is potentially problematic as it cannot necessarily be assumed that there will always be vents in locations that are always at either the closest or furthest points between two dwellings. Nevertheless, across a settlement in which dwellings are consistently close to their neighbours on average, it is assumed that proportionally more vents will be in close proximity to neighbouring dwellings than in a settlement where dwellings are not as consistently close together.

Under specific experimental conditions a material can be found to have a critical heat flux for ignition. If a design fire is known or estimated, this critical heat flux can contribute to the conceptualisation of a critical distance for ignition. In simple terms this is the maximum distance the material can be from a fire at which it will ignite. Wang et al. investigated this theory in relation to informal dwellings in Cape Town [25] and proposed a critical distance for ignition of as much as 3.3m if there are polyurethane-type materials exposed.

The proposed metric, ‘average minimum distance to nearest neighbour’ (*Sp*), is calculated by finding the minimum distance between each dwelling and its nearest neighbouring dwelling in the dataset, and then averaging the values for all the dwellings in each ISA (Figure 1).

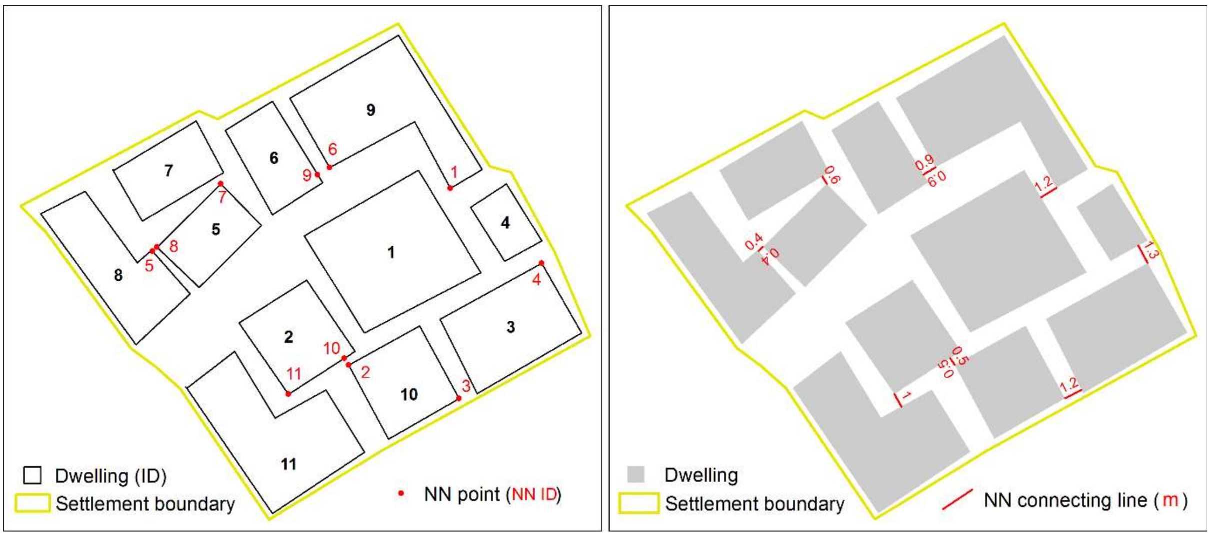

Figure 1:Method for finding the set of minimum distances from each dwelling to its nearest neighbour (NN), from which the metric ‘Sp’ is calculated

This metric simply conceptualises how fast a fire will be able to spread from the average dwelling in an ISA to its nearest neighbour, regardless of how many other dwellings it has the capability of spreading to. In accordance with the dimensional limits proposed by Wang, et al. for no through-draft conditions [25] it is therefore proposed that risk associated with dwelling spacing is at a maximum if the average minimum distance to nearest neighbour across all dwellings in an ISA (*Sp*) is less than 0.6m, and at a minimum if the average is over 3.3m, so:

$$X_{Sp} = \begin{cases} 1, & Sp < 0.6 \\ 0.6^2 \times \left(\frac{1}{Sp^2} - \frac{1}{3.3^2}\right), & 0.6 \leq Sp \leq 3.3 \\ 0, & 3.3 < Sp \end{cases} \quad (5)$$

2.2 Edge density

'Edge density' is a term that is used in many fields of work with varied definitions and applications. However, there are few, if any, instances of it being applied in any studies relating specifically to fire. In this context, it simply means the total length of dwelling edges per area of settlement, and was calculated accordingly (ρ_d). Currently, it is assumed that for an area of dwellings, a higher edge density implies more points from and to which a fire can spread. However, this does require more research in future. It could be possible that very high edge densities mean that the fire is more sheltered from any effects of wind. Furthermore, it is possible that, at increasing edge densities, the higher number of iterative 'jumps' between dwellings that a fire has to make results in slower overall fire spread.

Fundamentally, the concept of edge density, in this case, attempts to quantify the multi-directionality of possible fire spread from the average point in an ISA. The associated risk is modelled as a linear relationship with respect to the maximum value as calculated across all settlements in the dataset – a value of 0.63m^{-1}:

$$X_\rho = \frac{\rho_d}{\rho_{d,max}}, \qquad \rho_{d,max} = 0.63m^{-1} \quad (6)$$

2.3 Weighted average critical patch size

Whilst dwelling spacing and edge density may dictate the speed and multi-directionality of fire spread, the extent of spread should be limited by the size of the 'critical patch' in which the fire occurs. The critical patch is defined as the group of dwellings that all lie within a given critical distance of ignition of at least one other dwelling in the group. In theory, given unlimited time in the absence of external pressures (wind, firefighting etc.), a fire that originates anywhere in the patch should spread to all other dwellings within the patch, but no further.

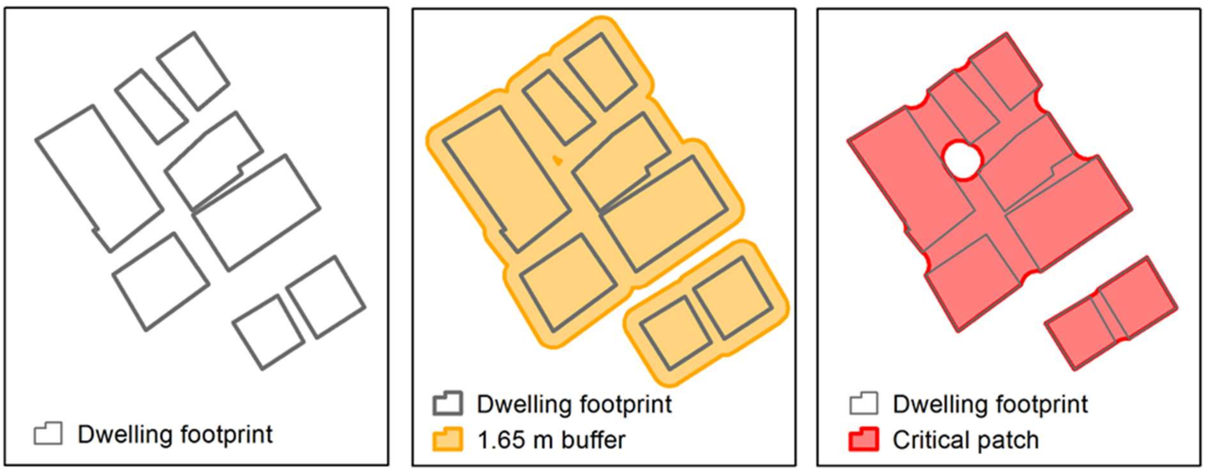

Figure 2: Method for producing critical patches using a 1.65m buffer, showing a group of eight dwellings resolves into two 'critical patches'

Again utilising the theory of critical distance, a set of critical patches was produced. All dwelling footprints were buffered out – that is to say, their boundaries were offset outwards in all directions – by 1.65m, so that the buffered dwellings would overlap if they were within 3.3m of each other. The critical distance of 3.3m is as per Wang et al. [25]. These overlapping buffered boundaries were then joined to create larger ‘critical patches’, which were subsequently buffered back by 1.65m so the extent of the patch was the outermost edge of the outermost dwellings in the patch. This process is shown in Figure 2. This approach assumes that polyurethane-type materials are present in all dwellings and so is a conservative calculation (for further discussion see 4.1.2). The weighted average area (A_{av}) of all resultant patches ($A_{p,i}$) across each ISA, where there are n patches in the ISA, was calculated:

$$A_{av} = \frac{\sum_{i=1}^{n} A_{p,i}^2}{\sum_{i=1}^{n} A_{p,i}} \tag{7}$$

A weighted average is proposed rather than a simple mean because the patch size indicates both the amount of ‘connected’ fuel and the probability that a fire is initially located in that patch (assuming the probability of ignition in any given dwelling is equal). It is necessary to use a weighted average to fully account for high risk that is present in ISAs with very large critical patches but also many isolated dwellings and smaller patches. For example, the ISA *Monwabisi Park B* has one critical patch of 91,600 m^2 but also many isolated dwellings. This results in a weighted average patch area of 71,000m^2 but a simple mean area of only 138m^2. This relatively tiny mean is clearly not reflective of the extent through which a fire could burn in the largest patch.

The risk associated with critical patch size is modelled as a linear relationship relative to the maximum weighted average, which happens to be the *Monwabisi Park B* value of 71,000m^2:

$$X_A = \frac{A_{av}}{A_{av,max}}, \qquad A_{av,max} = 71{,}000m^2 \tag{8}$$

2.4 Multiplicative model

Together these three metrics conceptualise risk associated with the average speed, multi-directionality and possible extent of fire spread across all points in an ISA. A simple multiplicative risk model is proposed to quantify the overall risk presented by a settlement’s layout:

$$X_{tot} = X_{Sp} X_{\rho} X_A \tag{9}$$

The final rankings and corresponding GIS dataset are available at [dataset] [26].

3 Analysis

Across the 291 ISAs that were evaluated for fire spread risk, the maximum risk score (X_{tot}) was 0.452, achieved by the Siyahlala – Du Noon ISA. For the purposes of comparing the risk model results with fire history data, the full set of risk scores were normalised with respect to this maximum value:

$$X_{norm} = \frac{X_{tot}}{0.452} \tag{10}$$

Normalising the data provides a means by which these risk scores can be mapped to similarly normalised quantitative data on the size of past fires. The City of Cape Town municipality collected fire incidence data over the period 2009-2015, and gave each informal settlement fire a grid reference by its location [8]. The full dataset comprises 401 1km × 1km grid squares (Figure 3). Using this data, the average fire size – by number of dwellings destroyed per fire incident – was calculated, with a maximum value of 70.77 dwellings.

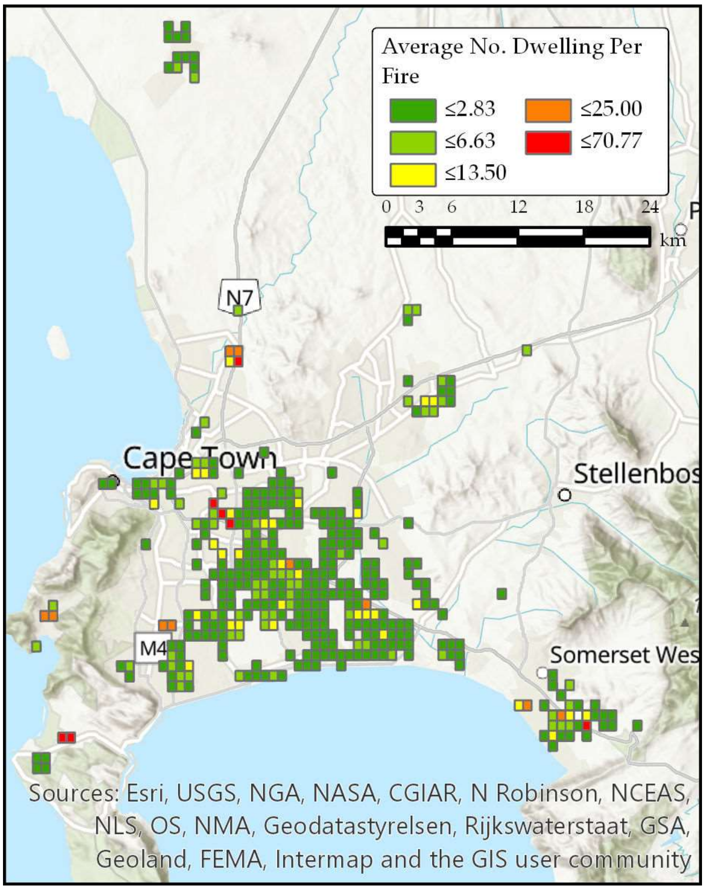

Figure 3 - Average fire size in number of dwellings destroyed per fire, from City of Cape Town fire incidence data for 2009-2015

Again, this data set was normalised for the purposes of comparison:

$$FS_{norm} = \frac{FS}{70.77} \tag{11}$$

Finally, sorting the ISAs and fire incidence areas by their ranks and normalising these ranks, the two datasets can be plotted against each other (Figure 4).

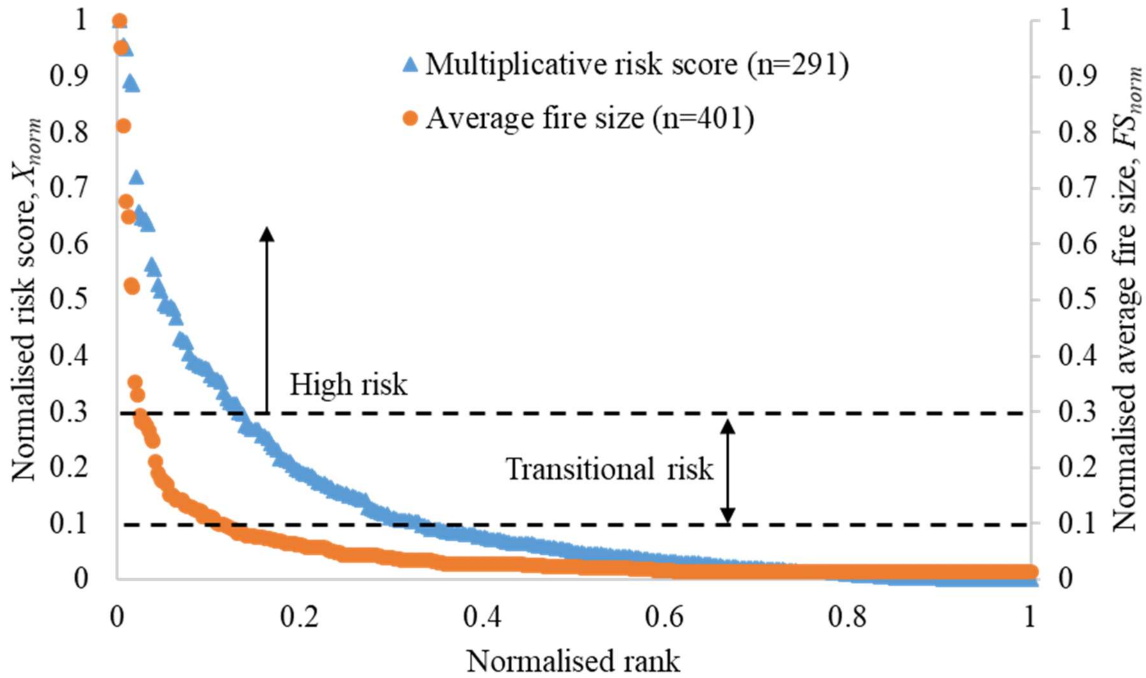

Figure 4: Normalised ranked distributions of 291 ISAs by multiplicative risk score, and 401 fire history data points by average fire sized

There are several reasons why direct numerical comparison or a regression model were not possible with the fire incidence data. Primarily this was due to the coarse mapping of the data to grid squares on a scale much larger than individual ISAs, so it could not be reliably attributed to specific settlements in all cases. Nevertheless, a clear trend is identifiable across both the risk model data and the fire incidence data: a very small number of settlements are responsible for the majority of large fires. In terms of risk, a minority of settlements contain the majority of fire risk.

3.1 Verifying risk

The predicted fire risk of selected highest ranked settlements can be compared with media reports of several large fires over the last decade (Table 1). The location of these settlements – and others that will be discussed – is given in Figure 5.

Table 1: Comparison of a selection of ISAs by risk model rank and past fire incidents

ISA	Risk Model Rank	Corresponding settlement	Fire details (date)
BM Section	4th	BM Section, Khayelitsha	800 dwellings, 3000 homeless (2013) [27]
Kosovo	5th	Kosovo	120 dwellings, 1400 displaced (2018) [28]
Dontshiyake	7th	Imizamo Yethu	2194 dwellings, 9700 homeless (2017) [2]
Wetlands	12th	Masiphumelele	1000 dwellings, 4000 homeless (2015) [5], 256 dwellings, 1000 homeless (2019) [29]
Doornbach	19th	Doornbach (Du Noon)	100 dwellings, 500 displaced (2018) [30]

The risk model, though simplistic, appears to very quickly identify settlements which exhibit the potential for fire to spread to hundreds of dwellings. This is due to these settlements ranking highly in all three of the proposed metrics. However, even among these high risk settlements there are large discrepancies in the size of past fires, ranging from 100-2000+ dwellings. Reasons for this are discussed in Section 4.

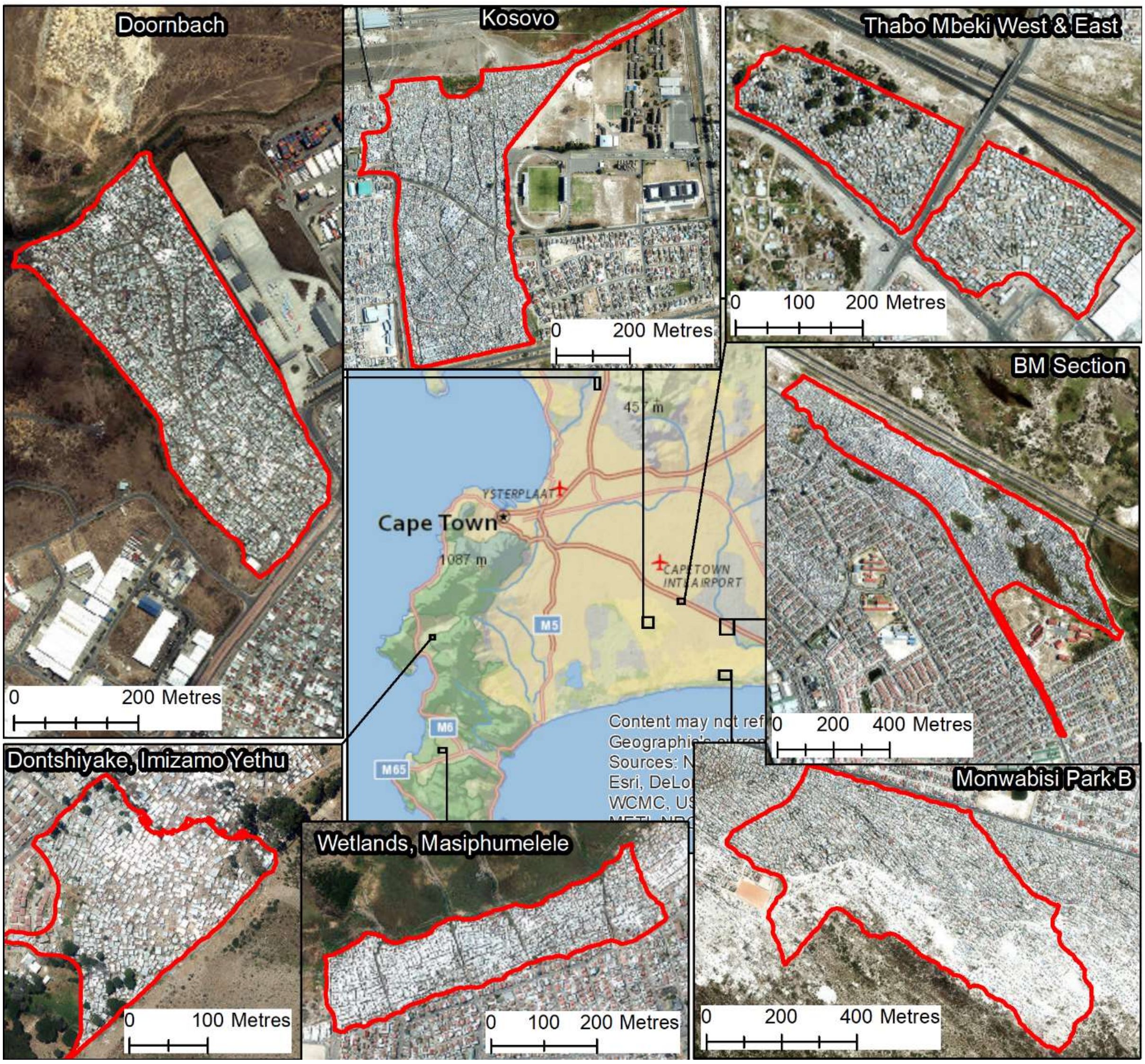

Figure 5: Selected ISAs – extents and their geographical locations

There are settlements which are ranked highly by the risk model that do not appear to have recently experienced any notably large fires. In some cases, whilst there are no media reports to suggest large fires, the high fire risk can be corroborated by the fire incidence data. For example, in addition to the 2018 Doornbach fire (Table 1), the Du Noon group of informal settlements experienced 59 fires with a total of 1163 destroyed dwellings at an average of almost 20 per fire from 2009-2015. The Du Noon cluster includes several smaller, low risk-ranked ISAs but notably also includes the ISAs Siyahlala - Du Noon; Doornbach; and Ekuphumleni - Du Noon 3, ranked 1st, 18th and 19th by the risk model respectively. It would be reasonable to expect that these ISAs account for the particularly high average fire size in the Du Noon area.

There are also settlements which are ranked highly by the model, yet have no corresponding media reports of large fires or notable evidence of large fires in the fire incidence data. Particularly prominent examples include BT Section and DT Section 1, both in Khayelitsha, ranking 2nd and 3rd for risk respectively. This would indicate that either the physical development of the settlements time that has brought them to a high risk status have happened fairly recently, or that they have simply been fortunate to experience ignitions at times when there have not been prime conditions for fire spread (see Section 124). However, both settlements have similar spatial properties (X_A, X_{Sp} and X_ρ) to other large ISAs in the Khayelitsha region, notably 4th ranked BM Section which experienced an 800 dwelling fire in 2013 (Table 1). This suggests that these settlements have a spatial arrangement of dwellings sufficient for the spread of large fires. Indeed , another Khayelitsha ISA, 30th ranked Silvertown ($X_{Sp} = 1, X_\rho = 0.540$), is compositionally very similar to DT Section 1 ($X_{Sp} = 1, X_\rho = 0.587$), and, despite being smaller, experienced a fire that destroyed 200 dwellings and displaced 4000 people in 2018 [31]. This highlights the fact that, whilst a settlement that has no apparent history of large fires, it may still be highly capable of allowing the development of large fires.

It can also be observed that ISAs which rank highly in one or two of the metrics will not necessarily rank highly for risk overall. This can also be compared against fire history with two key examples (both identified in Figure 5).

3.1.1 Monwabisi Park B

This ISA has been mentioned already due to it having the maximum weighted average critical patch size (i.e. $X_A = 1$). With one single critical patch of 91,600m^2 – resulting in a weighted average of 71,000m^2 – it would certainly seems that there is potential for the development of a very large fire. However, no media reports were identified that give any evidence of large fires here. Furthermore, the ISA lies exclusively within the spatial bounds of fire incidence data that indicates the average fire size is no more than 2.4 dwellings. This would suggest that the low edge density ($X_\rho = 0.333$) and average dwelling spacing ($X_{Sp} = 0.194$) contribute to an environment in which no fire has yet been able to spread fast enough in multiple directions for a mass conflagration. By the risk model, Monwabisi Park B ranks 78th for risk.

3.1.2 Thabo Mbeki

Thabo Mbeki settlement is composed of two ISAs. Both Thabo Mbeki East ($X_{Sp} = 1$) and Thabo Mbeki West ($X_{Sp} = 0.903$) scored highly for risk associated with dwelling spacing, but neither scored highly for patch size or edge density (

Table 2). This is indicative of a settlement with multiple smaller groups of dwellings spaced

ISA	Risk Model Rank	Normalised Risk Score (X)		
		A	Sp	ρ
Monwabisi Park B	78th	1	0.194	0.333
Thabo Mbeki East	46th	0.237	1	0.492
Thabo Mbeki West	69th	0.161	0.903	0.492

close together but no dominant critical patch to enable extensive fire spread. The ISAs overlay two fire incidence grid areas of average fire size 1.2 and 2.4 dwellings, indicating the average fire size for Thabo Mbeki is of a similar size. Past fires identifiable in media reports corroborate this, with individual reported incidents burning 2 and 7 dwellings each [32,33]. The two sections of the settlements are ranked 46th and 69th by the model, respectively.

ISA	Risk Model Rank	Normalised Risk Score (X)		
		A	Sp	ρ
Monwabisi Park B	78th	1	0.194	0.333
Thabo Mbeki East	46th	0.237	1	0.492

Thabo Mbeki West	69th	0.161	0.903	0.492

Table 2: Normalised component risk scores for selected ISAs

3.2 Large fire capability

Whilst this method is entirely based on quantifying risk rather than numerical modelling of fire spread, it clearly identifies the tendency for a limited number of fires to develop into large conflagrations due to settlement layout. It is proposed that there reaches a critical point in the layout, as quantified by the risk model, where a mass conflagration is possible. This behaviour can be viewed as a structure of conditions, namely that there is a high risk of large fire development in a settlement if,

1. the average dwelling is close enough to at least one neighbour to promote rapid fire spread, particularly if it is close enough for direct flame impingement ($X_{Sp} = 1$),
2. *And* there is a multiplicity of pathways ($X_\rho \rightarrow 1$) to allow many of these dwelling-to-dwelling interactions to occur at once,
3. *And* there is a large enough critical patch to allow the fire to grow to a size in which the dominant mechanisms of fire spread become less dependant on individual dwelling-to-dwelling interactions.

The key condition here is Condition 3 since the fundamental dynamics concerning this shift in spread mechanisms are not yet known, they are merely proposed based on observations that large fires in informal settlements exhibit wildfire-type spread [5]. In basic terms, it is hypothesised that, in the right circumstances, a fire transitions from burning as discrete blocks of fuel (the individual dwellings) to burning as if in a semi-continuous bed of fuel.

It is difficult to recommend a specific point of criticality in terms of the risk model. Rather, the criticality may be better defined by a transitional zone (Figure 4), in which a fire in an ISA with 'transitional risk' would not be expected to develop wildfire-type characteristics if left alone, but may do so under the influence of a variety of other spatial risk factors as discussed in Section 4.

3.3 Objective limits of risk

The risk model can be reverse engineered to establish what conditions physically constitute the concept of 'high risk'. This is important given the metric values for settlements will change over time as they grow or densify. As such, the maximum reference values for patch size and edge density will change, altering the basis of the entire model. Real, physical limits of risk are proposed so that, in future, risk can be defined objectively. Intuitively, the highest ranked ISAs have an average minimum distance to nearest neighbour of less than 0.6m (i.e. within the distance for flame impingement even in the absence of wind), with the first to exceed this ranked at 54th by the model (Figure 6).

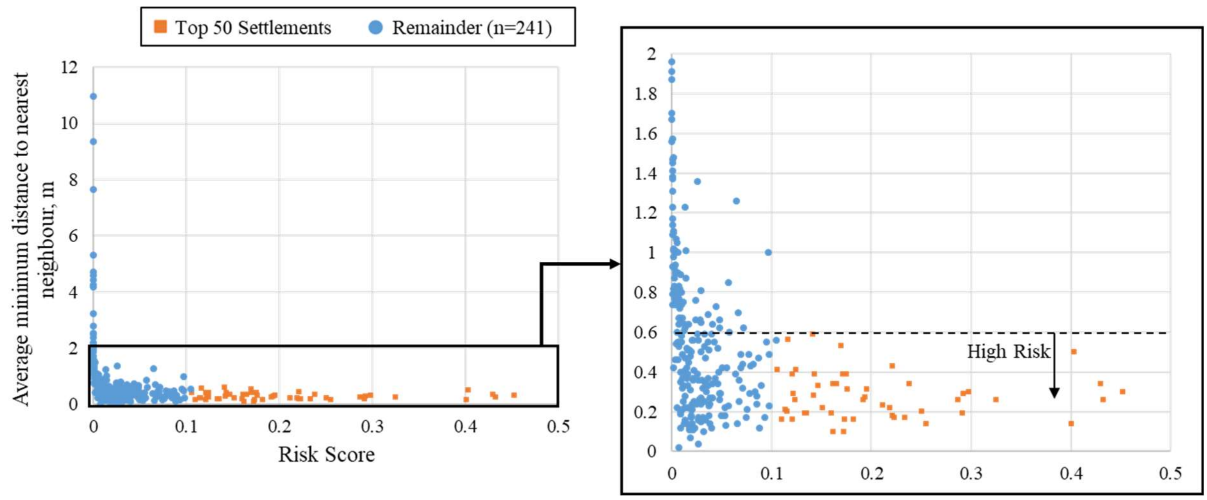

Figure 6: Variation of average minimum distance to nearest neighbour (Sp) with risk score, showing proposed objective limit of risk and highlighting settlements where Sp≤2m

Observationally, the top 50 settlements all have weighted critical patch areas of at least 10,000m^2 (1 ha) and edge densities of at least 0.3m^{-1} (Figure 7). It could therefore be proposed that settlements are objectively at high risk if they conform to these three limits, however these should be applied with caution outside of the specific context of Cape Town prior to further research.

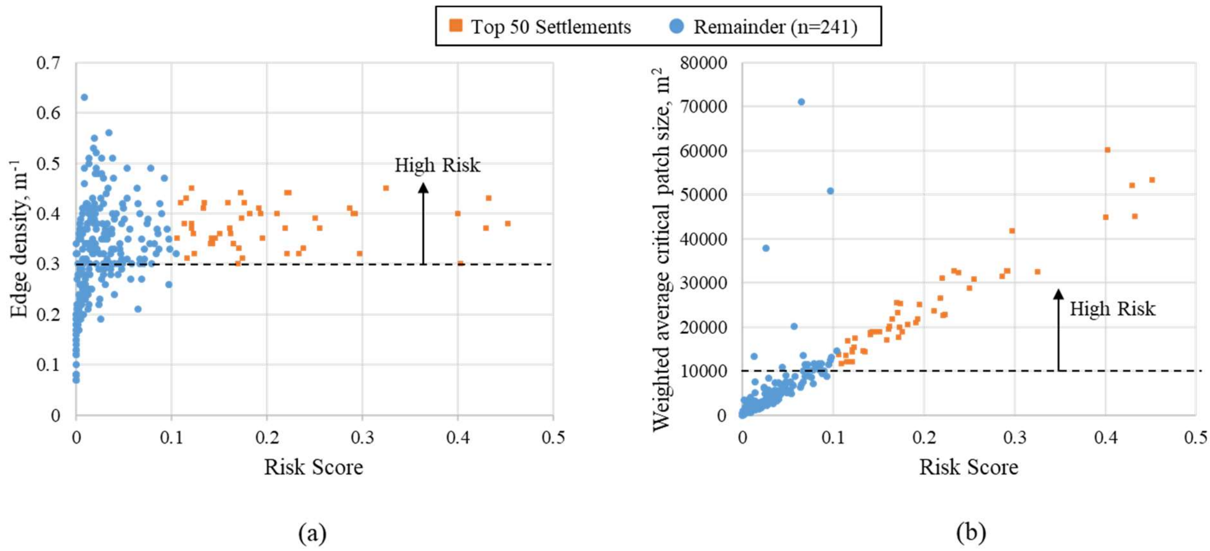

Figure 7: Variation of (a) Edge density and (b) Weighted average critical patch size with risk score, showing proposed objective limits of risk

4 Wider framework of fire risk

The basic layout of a settlement, quantifiable by the above risk model, establishes if that settlement is capable of sustaining a large conflagration. However, there are additional factors that can contribute to the overall outcome of a fire. It is proposed that settlements are, in fact, subject to three sources or layers of risk – the layout and composition of the settlement, the provision and quality of infrastructure, and the natural environment. Each of these layers is composed of several distinct spatial features (Table 3).

Table 3: Spatial fire risk factors by category

Layout and Composition	Firefighting infrastructure	Natural Environment

Dwelling spacing Edge density Critical patch size Fuel load Building materials Settlement shape	Road access Proximity to fire stations Fire hydrant provision and functionality	Wind speed Wind direction Climate Topography

Quantifying how these factors may contribute to fire risk is complex, due to lack of understanding, or lack of data that is of sufficient quality and resolution. Yet, they contribute to the overall spatial context of any given fire so they must be considered. As will be discussed, however, it can be difficult to fully dissociate the additional risk imposed by these factors from the internal layout of the settlement.

4.1 Layout and Composition

4.1.1 Fuel Load

The actual fuel that is burning must be acknowledged when discussing fire risk, however quantifying the risk imposed upon the wider settlement is challenging. Firstly, the degree of variability of fuel load in individual dwellings is high. One estimate in South Africa puts the fuel load at 410MJ/m^2 with a 140MJ/m^2 standard deviation [34], but this figure may be as high as 2000MJ/m^2 if residents are storing fuels, firewood or tyres in their home [5]. Quantifying this remotely is challenging, and visiting even a single settlement to obtain data would be time consuming. Furthermore, the effect of fuel load partly depends on the layout of the settlement. The fuel load will determine how long an individual dwelling burns, but not how fast the fire can spread. Spread rate is heavily dependent on dwelling spacing. Data from experimental tests with dwellings spaced at 1m showed that fire spread between dwellings tended to occur approximately 2-4 minutes prior to the burning dwelling collapsing [7] (and collapse does not necessarily mean all fuel has been consumed). Fundamentally, the impact of fuel load decreases as dwelling spacing decreases. At greater dwelling spacings, a low fuel load may mean a dwelling burns out before the fire can spread, but in such a situation the fire spread is likely to be slow in the absence of wind, so risk is already not particularly high.

4.1.2 Building materials

Building materials play a dual role in informal settlement fires. They contribute fuel in addition to the contents of the dwelling, thus influencing its burn time. However, more importantly, since the building materials form the exterior of the dwelling, they are generally the first point of ignition in dwelling-to-dwelling fire spread. This is a complex issue beyond the scope of this paper but readers are referred to Cicione et al. [7] for more detail. The use of the critical distance from Wang et al. [25] as a metric for calculating risk imposed by both dwelling spacing (X_{Sp}) and patch size (X_A) relied on the assumed presence of plastic materials, but the critical distance is reduced, in theory, if there are no plastics present. Similar to fuel load, obtaining the necessary data for this would be time consuming and difficult to do remotely. Using a critical distance of 3.3m [25] provides a conservative, worst case, estimate of risk.

4.1.3 Settlement shape

It is also proposed that the shape of a settlement may have some bearing on the outcome of a fire. When a fire reaches an adequate boundary its progress can be easily stopped. A suitable boundary might be imposed by obstructions such as a road or vacant land. The 2015 Masiphumelele fire was stopped at wild land at the edges of the settlement and a canal [5] and the 2017 Imizamo Yethu fire had reached the upper edge, before the wind changed direction and drove the fire back into the settlement [2]. If the wind direction had not changed, the fire may have been able to move into vegetation at the boundary, but it would have at least moved out of, and beyond, any inhabited land. Generally, if a settlement has a high proportion of impassable boundaries compared to the area of the settlement, there is a good chance the fire will reach a boundary and be stopped. However, more work is needed to be able to quantify this for several reasons. Primarily, what constitutes an impassable boundary is not yet fully defined, and is difficult to identify remotely. Furthermore, the effect of settlement size in relation to settlement shape has also not been investigated. In a real fire, the effects of settlement shape also depend largely on where the fire starts and the wind direction.

4.2 Firefighting infrastructure

The risk imposed by infrastructure (or lack thereof) is a result of how effectively the fire service are able to combat a fire given the resources available to them. GIS analyses could be useful for quantifying fire service travel time, road access and quality, and fire hydrant availability. Spatial metrics such as the travel distance of a settlement to the nearest fire stations, and the average distance of dwellings to their nearest accessible road and fire hydrant may be helpful quantifiers of risk [35]. However, the true risk must also take into account that the response of the emergency services can be affected by settlement conditions and interactions with residents. For example, a quick arrival of the fire service may be negated if access routes to the fire are blocked and fire hydrants are not serviceable. It is important for the fire service to be notified immediately when a fire is discovered which requires correct contact information to be disseminated publicly. However, a recent survey of one settlement in Cape Town revealed that less than 70% of residents knew an emergency services contact number and less than 9% knew the direct fire brigade telephone number [36]. Readers are referred to the work of Kahanji et al. on the Imizamo Yethu fire of 2017 [2] for a more detailed study into the complex and dynamic scenario faced by the fire service. Overall, concerning firefighting infrastructure, it is challenging to incorporate purely spatial metrics in a risk model without considerable further research.

4.3 Environment

4.3.1 Wind

Wind clearly has a dominant role in fire spread. For the Cape Town fire data from 2009-2015 [8], informal settlement fires that took place in winds that were anecdotally described by the fire service as ‘gale-force’ or ‘strong’ burned an average of 28 dwellings, though with standard deviations of 65 and 113 respectively, suggesting a very high variability. However, fires during ‘moderate’ wind or ‘light breeze’ burned only 11 and 4 dwellings on average, respectively. In the Imizamo Yethu fire of 2017, the wind was strong enough to push the fire downhill [2], a slope with maximum pitch of approximately 15° [20].

The effects of wind are complex. At the dwelling level, high winds can delay flashover by increasing the heat release rate required to initiate it [37]. However, once a fire is fully developed, wind-assisted through-draft increases both the length of flames projected from openings and the heat flux imposed upon adjacent dwellings [25]. Local interactions of the wind with the dwelling surfaces could increase or decrease flame length and must be taken into account. Furthermore, it is reiterated that fires may develop wildfire-type characteristics, meaning that as a fire develops so does the effect of wind. In the field of wildfire, the role of wind has been conceptualised in many ways. Across a variety of studies reviewed by Sullivan [38], the relationship between wind speed and fire spread rate has been previously modelled by many different exponential and power functions. Experimentally, it has been shown that both flame length and rate of spread of a line fire in a wildfire-type fuel bed increase exponentially with wind speed [39].

4.3.2 Climate

It is assumed that moisture has some effects on informal settlement fires but it not known how best to quantify this. It may involve quantification of rainfall or humidity, either of which are easily done, but the subsequent relation to fire risk has not been established. Generally, the presence of moisture will vary with seasonal changes in climate, making it difficult to discern the role of moisture independently given the significance of wind which also varies in seasonal patterns.

4.3.3 Topography

Flame spread rate is known to increase with fuel orientation (slope angle) but the exact relationship depends on the context (for basic examples see Drysdale [24]). Experimental tests suggest there is an approximate linear, but shallow, increase in flame spread rate with slope angle up to a transitional point where the burning regime changes and flame spread increases exponentially. This change does not appear to occur at slope gradients below 30% (16.7°) [40,41], but likely occurs at gradients of approximately 45% (25°) [41]. This is contextually relevant, given that few of Cape Town's informal settlements are located on steep slopes. Using available open source data [20], it was found that none of the informal settlements have an average slope exceeding 19°. Indeed, the vast majority (92%) have average slopes of less than 5°. Further work is required, as this analysis assumes that the informal settlement will act as a fuel bed (like wildfire spread). Currently, it is unknown how slope affects fire spread in the urban context, particularly in dwelling-to-dwelling interactions.

There is also the possibility that the effects of topography are negligible in the overall context of fire spread. In the Imizamo Yethu fire, the wind was dominant in controlling the fire spread and pushed the fire downslope [2], at an angle of approximately 15° (27% gradient).

4.4 Additional risk

In addition to the risk model, these factors act as sources to exacerbate fire risk. Whilst much work is still required to understand their effects and incorporate them into a numerical model, a conceptual framework for understanding their basic function is laid out in Figure 8. Each additional risk factor contributes to overall risk as a function (as yet undefined) for which the internal risk is an input. In line with prior discussion (4.1.1-4.3.3), there are clearly instances where the layout of a settlement determines that there is no additional risk as a result of particular factors. In simple terms the internal risk defines the starting point for a pathway through additional risk layers. Three hypothetical examples are given to illustrate this (Figure 8):

1. A fire in an extremely low internal risk settlement. Fire spread from a single dwelling is very unlikely so the shape of the wider settlement and availability of hydrants are effectively irrelevant. The effect of wind on compartment fire dynamics and the length of burn of the initial dwelling due to fuel load may be determining factors in the fire being able to spread to 1-2 other dwellings at most.
2. A fire in a 'transitional' settlement. The outcome of the fire is dependent on all factors. A perfect storm of conditions may result in a fire that spreads to tens of dwelling. Wind plays a role in the initial compartment fire dynamics but also subsequent fire spread as a flame front develops.
3. A fire in a very high internal risk settlement. Left to its own devices, this fire will naturally develop into a wildfire-type conflagration. Dwellings are in such close

proximity to one another that a) the effects of wind on individual compartment fire dynamics have a negligible influence on the rate of spread, b) the interaction of the wind with the fire will be in a manner similar to wildfire dynamics, and c) the fuel load in dwellings is irrelevant since the fire spread vastly outpaces dwelling burnout time regardless of low fuel loads.

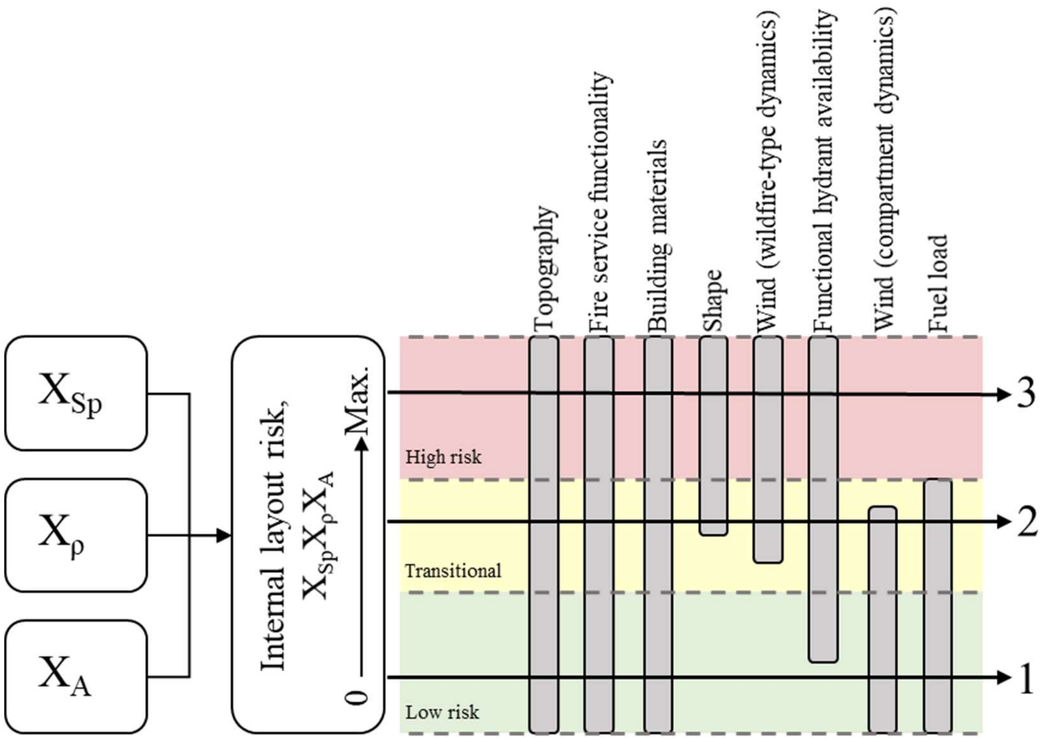

Figure 8: Conceptual framework for additional levels of fire risk, where the pathway of risk is determined by a point of origin relative to the conditions of settlement layout

The upper and lower operating limits of a factor's function in the framework are simply for illustration and do not represent exact limits. They are merely to show the concept that they remain relevant only to a point, depending on the layout of dwellings. There are three factors deemed to effect all fires regardless of internal risk: topography, building materials and fire service functionality. At this stage it is safest to assume they play a role in all fires as their effects are difficult to quantify cleanly, if at all. Overall, it is hypothesised that, where internal risk quantifies the ability of a settlement to develop a large fire, additional risk factors are what result in the large variability in historical fire size in high risk settlement (refer to Table 1).

4.5 Fire risk development with time

4.5.1 Settlement layout

Clearly, this analysis, in which multiple factors can have highly-varying effects on the outcome of a fire, presents issues. It implies there is no one-size-fits-all solution to tackling the issue of fires. However, given the settlement layout can be identified as being significant in its own right as well as influencing the effect of additional environmental and infrastructural factors, it provides a basis for tackling the problem. Consider a hypothetical objective risk model in the style of the earlier multiplicative risk model (Figure 9).

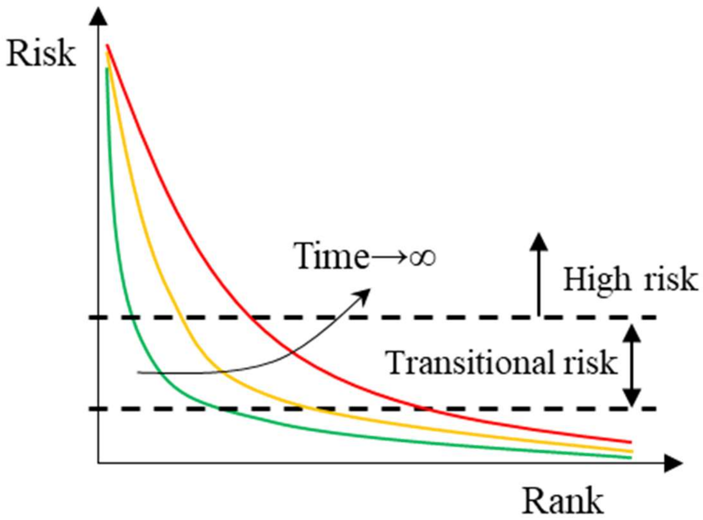

Figure 9: Development of fire risk in time for a hypothetical risk model, if settlements are allowed to densify

An obvious concern is that as settlements grow and densify in time, more settlements will move into transitional and high risk zones. It is therefore proposed that the development of measures to improve the settlement layout will be critical to inhibiting the development of large fires. Implementing such measures will likely be tricky given the nature of the problem – that settlements are already established and wholesale changes to a settlement would require uprooting many residents. However, the component metrics of the risk model at least identify some of the fundamental variables by which small changes could result in increases in safety. For example, the approach developed by Wang et al. [25] that is built into the concept of critical distance for fire spread in the risk model relies on assuming the such variables as the type of materials present and the dimension and orientation of windows. If incremental changes can be made over time which target a settlement's specific vulnerabilities, such as identifying and removing materials with low critical heat fluxes and ensuring that doors and windows are oriented away from neighbouring dwellings, then fire risk can be reduced.

4.5.2 Firefighting infrastructure

As discussed, the evaluation of fire service response based solely on spatial metrics is unreliable. However, this does not negate the importance having high-quality, functional infrastructure. Rather, rigorously maintained infrastructure should provide the basis upon which the fire service can operate. Over extended periods of time this should include:

- Construction and maintenance of adequate access roads to and within informal settlements, including monitoring to prevent the occurrence of obstructions to fire engines,
- Monitoring of fire hydrants to ensure they are functional and accessible within settlements,
- Dynamic allocation of resources to fire stations to ensure efficient distribution of firefighting capability relative to the present risk in nearby informal settlements.

Additionally, to ensure an effective and productive relationship between residents and the fire service, there is a need to provide accessible information on fire safety and clear public dissemination of the correct emergency service telephone numbers.

4.5.3 Environment

Given the continuation of global warming, the effects of the environment on informal settlement fire risk, which are already complex, are unpredictable over long periods of time. Not only will changing weather patterns alter the probable conditions which will drive the physical spread of fire, but changes to seasonal temperature variations may impact upon the actions of residents in heating or cooling their homes. This could include the usage of different energy sources, possibly resulting in increased fire ignitions, or it could mean residents start incorporating new, potentially hazardous, building materials into their homes to cope with new climatic conditions. A simple example might be that a hypothetical increase in the occurrence of heavy rain showers results in a higher prevalence of residents using plastic sheeting as waterproofing. There is a great deal of uncertainty into what, when and how changes will occur, but a pre-emptive understanding of the impact of climate conditions on fire should contribute to risk mitigation strategies that can respond quickly to future climate changes.

5 Conclusions

The layout of informal settlements are critical in determining the settlement's ability to develop large-scale fire spread. Metrics to establish this criticality have been proposed, taking into account the fundamental ability of a fire to spread quickly, in multiple directions, and to a sufficiently large extent. However, it is suggested more work is needed to refine these metrics and better understand how they relate to the physical dynamics of fire spread. For example, it is not yet known at what size of fire the fire spread behaviour may be more adequately described as wildfire-type spread. Future work could take the form of experiments, computational modelling or a combination of the two, and needs to aim at developing knowledge of the fundamental fire spread mechanisms and processes involved in informal settlement fires. In the interim, the risk model methodology proposed in this paper provides a quick method for establishing the highest priority settlements for fire risk mitigation strategies across a set of settlements (regional or citywide).

Yet, the layout of a settlement does not independently determine the outcome of a fire. Additional risk factors, in unfortunate combinations, can contribute to the destruction of hundreds or thousands of homes in a single fire – particularly in instances of high winds. The variety of different risk factors establishes a need for an integrated approach to tackling the issue of informal settlement fires. The baseline risk posed by the settlement layout requires a great deal of physical engineering to prevent the establishing of large fires, but this alone cannot completely solve the problem. Both within and outside of settlements, the management and maintenance of wider firefighting infrastructure is required. Beyond the physical urban environment, sociological solutions are also required. This could include educating residents about best practice to prevent ignitions, and fostering good relationships with the fire service so residents are compliant and not problematic in fire scenarios. Generally, it should not be forgotten that the problem of fire is a result of the background of socio-economic deprivation, which must be combatted holistically and cannot be treated solely as an engineering issue. The engagement of policymakers with all types of expertise is therefore vital in progressing towards the most effective solutions. The provision of risk quantification methods for the use of policymakers should represent a foundation upon which they can engage with the issue.

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(https://web1.capetown.gov.za/web1/opendataportal/DatasetDetail?DatasetName=Aerial%20 photography), however, the City of Cape Town does not warrant or guarantee the quality or accuracy of the data, accessed, extracted and/or used from this site. Informal settlement area boundaries are as provided by the South African National Space Agency (SANSA).

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